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Full Length Research Paper

A comparative study of predicted and actual pore pressures in Tripura, India

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Past well drilled data in Tripura Region confirmed the existence of super pressure regime below the Middle Bhuban formation. In most of the areas, Middle Bhuban is capped by the Tipam, Bokabil and Upper Bhuban formations. But on the top of the Atharamura anticline, it is exposed to the surface offering less sediment thickness and huge risk for drilling. Exposure of Middle Bhuban escalates the possibility of over pressures at shallow depths and may lead to blowouts if the well is not properly planned. Pore pressure prediction is essential to understand the pressure succession in Atharamura Region. In this work pore pressures were predicted from seismic velocities at the synclinal and flank part of the Atharamura anticline and over pressured zones are identified. When the predicted pore pressures were compared with offset well pore pressures, an excellent match is observed with the offset wells measured pore pressures. The observations which lead to the new level of understanding in selecting the prediction method and regional pore pressure profile were discussed in this paper.

Key words: Middle Bhuban, Atharamura anticline, seismic velocities, pore pressure, offset wells.

INTRODUCTION

Pore pressure or formation pressure is the pressure experienced by the pore fluids in the pore spaces of subsurface formations. At any depth the overburden pressure is the summation of weight of grains and pore pressure.

In normal pressurised formations, porosity decreases with depth as the pore fluids are expelled out of pores due to the increasing over burden weight. Thus, this pore fluid expulsion maintains the effective communication of pore fluids with the surface. So at any depth pore pressure is simply the same as the hydrostatic pressure (1.03 g/cm^3 or 0.433 psi/ft) of the water column. In other words, pore pressure in normal compacted sediments is entirely due to the density and height of the fluid column.

In abnormal over pressured formations, the pore water expulsion is intercepted by rapid sedimentation and the absence of permeable pore networks. Thus, when the pore fluid experiences pressure above the normal hydrostatic pressure (1.03 g/cm^3 or 0.433 psi/ft), over pressure or super pressure develops (Burgoyne et al., 1991). In other words, the moment the pore fluid starts Bearing the weight of the overlying sediments over pressure develops (Burgoyne et al., 1991).

Knowledge of pore pressure is vital in deciding the drilling mud weight to be used. Drilling mud in the borehole creates hydrostatic head to balance the formation pressure during drilling.

In the absence of offset well data seismic, velocities are the only available pre-drill tools to estimate the formation pressures. Though the pore pressure prediction has the history of five decades, preciseness of wildcat pore pressure predictions are still in wide range of uncertainty. Pore pressure prediction in geologically challenging areas such as anticlines and fold thrust faults combined with possibility of abnormal pressures elevates this prediction to a high level of uncertainty (Swarbrick et al., 2010). This paper discusses the pore pressure prediction in such kind of challenging candidate where abnormal pressures are frequent.

OVER PRESSURE PREDICTION

Identifying the over pressured zones in drilling is crucial as it narrows the available drilling mud window. Drilling under tight mud windows increases the possibility of either fracturing of the formation or inviting blow outs. Pore pressure prediction is not only important in deciding

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the mud weight, but also to determine the number of casing strings and casing seat selection which have the huge impact in well integrity and economics. Proper understanding of the pore pressure can reduce the well cost and can help to plan a safe well.

The main over pressure causes are under compaction, fluid expansion, fluid migration and tectonics (Swarbrick and Osborne, 1998). Pore pressure prediction methods preciseness is based on their capacity to account for the causes of the above over pressure.

Terzaghi and Peck (1948) related the pore pressure with over burden pressure as

$$\sigma_{ob} = \sigma_v + \propto P_p \quad (1)$$

Where,

σ_{ob} = Overburden pressure, psi σ_v = Effective vertical stress, psi

P_p = Pore pressure, psi $\propto = 1 - \frac{C_r}{C_b}$

$\propto$ = Poroelasticity constant or Biot's constant, ($0<\propto<1$)

C_r = rock matrix compressibility, C_b = bulk compressibility of rock.

Terzaghi experimentally found that poroelasticity constant can be taken as $\propto = 1$ (Baker, 1996). Hence here we considered unit poroelasticity constant. From Equation (1) it is obvious that to calculate pore pressure we must first calculate over burden pressure and vertical effective stress. Generally, overburden pressure is calculated from bulk density of formation by the following equation,

$$\sigma_{ob} = \int \rho_b \, dD \quad (2)$$

Since the bulk density of the formation can be derived from offset well log data or from seismic velocities by using empirical relations (Gardner, 1974), overburden pressure can be easily quantified. But quantifying effective vertical stress is huge challenge and all the pore pressure prediction methods aim to unlock this challenge. The general approach in all the over pressure prediction methods is to measure properties of the subsurface formation and compares it with normal pressurised formation properties. Dutta and Ray (2002) found that over pressured formations exhibit the following discrepancies compared to the normal compacted formations.

(1) Higher porosities,
(2) Lower bulk densities,
(3) Lower effective stresses,
(4) Higher temperatures,
(5) Lower interval velocities, and
(6) Higher Poisson's ratio.

PORE PRESSURE PREDICTION –PAST WORK

Most of these overpressure discrepancies can be observed in seismic velocity, sonic log velocity responses and can be quantified as the deviation from the normal responses. So the development of normal compaction parameters plays a vital role in determining the reliability of the pore pressure prediction. Mostly pronounced pore pressure prediction methods are Hottmanand Johnson, Equivalent depth, Eaton and Bower's methods.

The first prediction approach by Hottman and Johnson (1965) method is still used in the industry due to its preciseness in pore pressure prediction. This method utilises calibrated sonic log velocities from offset well data and estimates the pore pressure for the proposed drilling location by linear regression.

Equivalent depth method (Ham, 1966) is based on the reasonable assumption that formations having same interval velocities would have the same effective vertical stress irrespective of the depth (Figure 1).

Eaton's method (Eaton, 1975) approximates the effective vertical stress with ratio of sonic log velocities and resistivity values (Figure 2). The modified Eaton's equation for variable overburden gradient is

$$P_p = \sigma_{ob} - (\sigma_{ob} - P_{p\,normal})\left(\frac{V_{observed}}{V_{Normal}}\right)^3 \quad (3)$$

$$P_p = \sigma_{ob} - (\sigma_{ob} - P_{p\,normal})\left(\frac{R_{observed}}{R_{Normal}}\right)^{1.2} \quad (4)$$

Where

$V_{observed}$, $R_{observed}$ = Observed values of interval velocity, resistivity at the depth of interest

V_{Normal}, R_{Normal} = Values of interval velocity, resistivity if the formation is compacted normally at the same depth.

Bower's (1995) approach shows the importance of accounting for causes of over pressure. Further, he shows where the equivalent depth will work and where it will fail. Based on his work, Bower proposed a modified approach which uses two different equations to quantify the over pressure by under compaction (Virgin curve equation) and by Fluid expansion (Unloading curve equation).

Virgin curve equation: $V = 5000 + A\sigma^B$ (5)

Unloading curve equation $: V = 5000 + \left(\sigma_{max}\left(\frac{\sigma}{\sigma_{max}}\right)^{\frac{1}{U}}\right)^B$ (6)

Where

V = interval velocity $\left(\frac{ft}{s}\right)$, σ_v = effective stress(psi)

A, B = constants from offset velocity Vs effective stress data

U = plasticity of the sediment ranges from 3 – 8

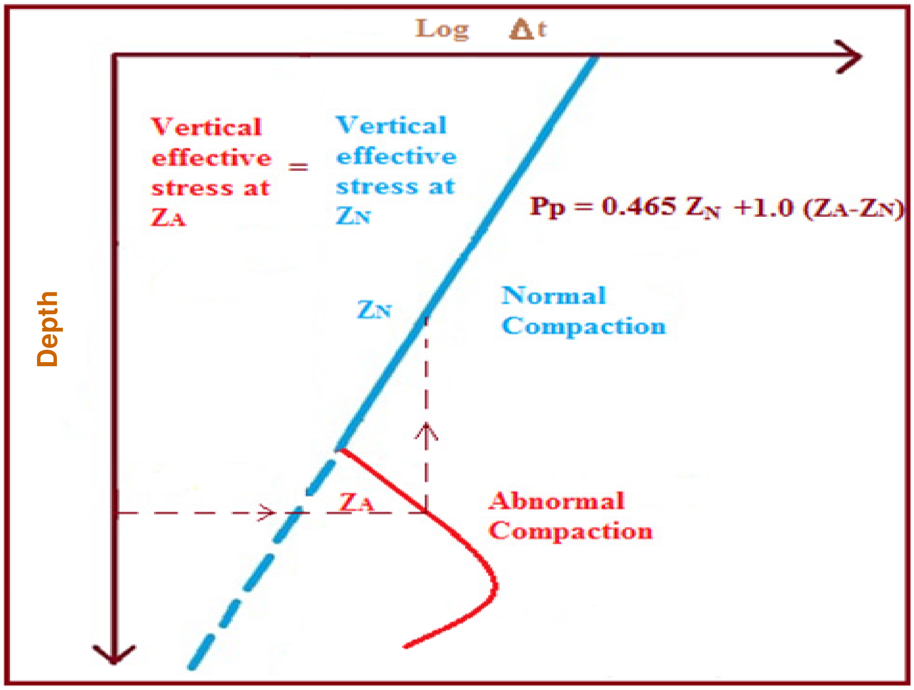

Figure 1. Equivalent depth method- Graphical procedure.

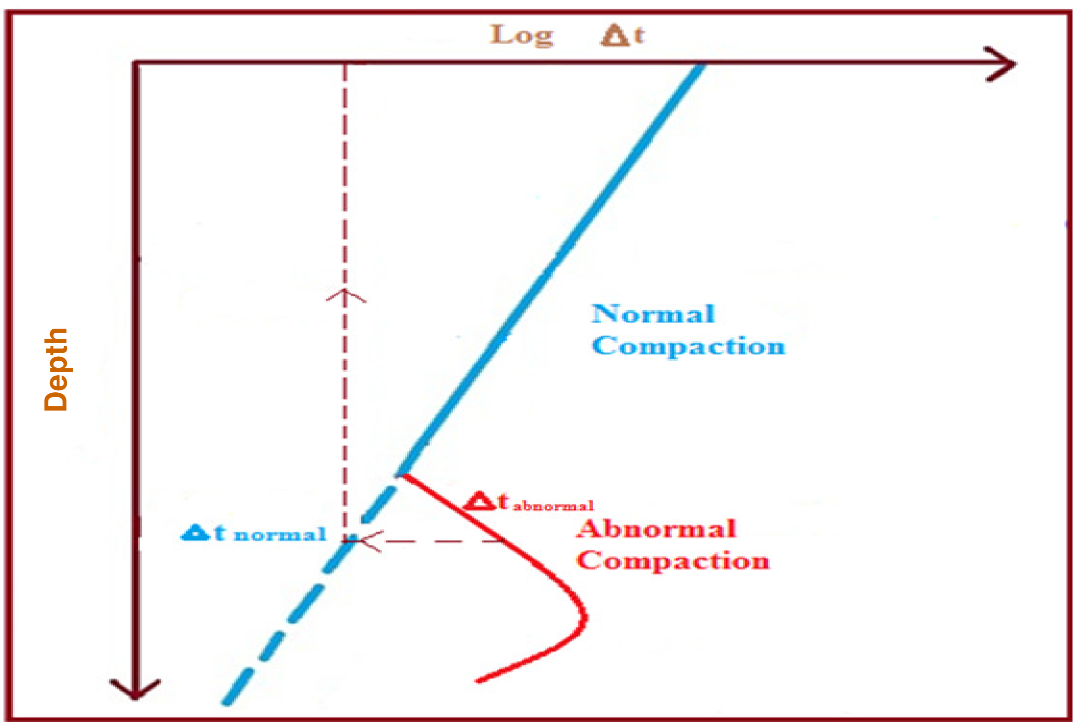

Figure 2. Eaton's method-Graphical procedure.

Bower showed that failure to predict the unloading of effective vertical stress may lead to overestimation of vertical effective stress on the cost of underestimation of pore pressure.

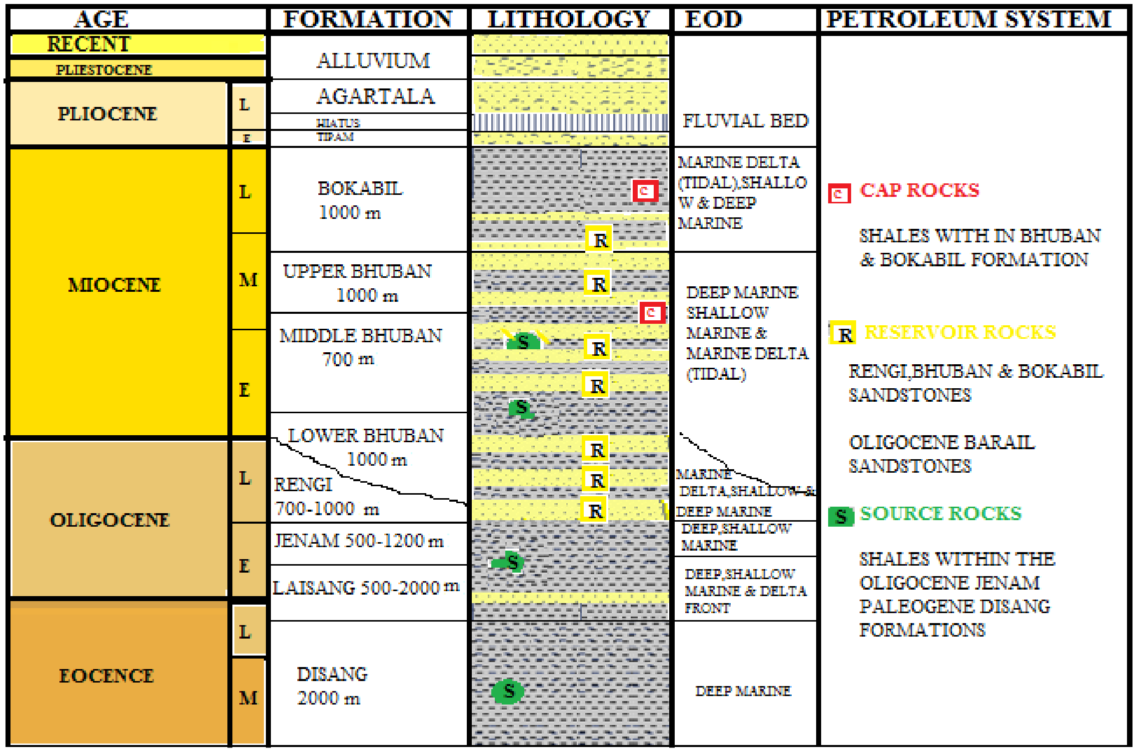

Figure 3a. General stratigraphy of Tripura.

STUDY AREA

Frequently encountered overpressures in the Gulf of Mexico have been particularly well studied and observed, but the phenomenon has been observed in many other places, including the North Sea, the Caspian Sea, Pakistan and the Middle East and Eastern parts of India. Thus the study area considered here is located in North-eastern part of India, Tripura. Tripura sub-basin is a part of Assam-Arakan fold belt thrust, is characterised by an alternating succession of ridges, valleys and is dominated by the series of anticlines. In most of the anticlines Middle Bhuban formation is capped by Upper Bhuban, Bokabil and Tipam formations (Figure 3a). High abnormal to super pressures are observed from Middle-Lower Bhuban, practically in all the structures of the Cachar area with pressure gradient reaching to almost geostatic or even exceeding. Compaction disequilibrium, aided partly by clay diagenesis and tectonic activity, has been found responsible for generation of over pressures in Tripura area (Sahay et al., 1998).

From the past well drilled data in the Tripura Region, super pressure regime below the middle Bhuban is confirmed, but not a single well is drilled in the deeper depths of Middle Bhuban due to well control problems. Unlike other anticlines, in Atharamura anticline Middle Bhuban is exposed to the surface and increases the possibilities of over pressures at shallow depths.

Prediction approach

Over burden pressure prediction

By the time-depth conversions (Pennebaker Jr. 1968), formations depths having different acoustic impedance can be found. From the interval travel time data, formation interval density was found by the following formula (ENI, 1999).

In terms of interval velocity:

$$\rho_{b,i} = \rho_{max} - 2.11\left[\frac{1-\frac{V_{int,i}}{V_{max}}}{1+\frac{V_{int,i}}{V_{max}}}\right] \quad (7)$$

In terms of interval transit time:

$$\rho_{b,i} = \rho_{max} - 2.11\left[\frac{\Delta t_{int}-\Delta t_{max}}{\Delta t_{int}+\Delta t_{f}}\right] \quad (8)$$

Where

V_{int} ,V_{max} = interval and matrix velocities of the formation (m/s)

Δt_{max} ,Δt_f = interval transit time in the rock matrix and fluid (μs/ft)

Then the overburden pressure is calculated simply by the following equation,

$$P_{ob} = \sum_{i=1}^{N} P_{ob,i} = \int \rho_{b,i}\, dD \quad (9)$$

Table 3. Predicted pore pressures match with measured pore pressures.

Well name	Number CDP points on the syncline showing match with the drilled well	Number CDP points on the flank showing match with the drilled well	Overpressure starts at (m)
Tichna	2	1	2400
Kunaban	1	1	3000
AD-6	No match observed	1	3200
Khubal	1	No match observed	1600
Agartala Dome	No match observed	1	3200
Kathalchari	3	1	2000

Selection of pore pressure prediction method

On available methods Bower and Eaton's methods predictions are well known for their accuracy. But the real constraint in the selection of prediction method is availability of data. As the Tripura sub-basin is starving of extensive exploration work, offset well data required for the Bower's method are readily not available. So here Modified Equivalent depth and Eaton's methods are used to predict the pore pressures and the predictions are compared with offset well measured pore pressures, with outcomes discussed.

Modified equivalent depth method

The modification implemented here was variable overburden gradient instead of unit overburden gradient. Thus, it makes the reasonable assumption that in abnormal pressured formations the excess overburden is solely carried by the pore fluids. This assumption can allow the effective vertical stress to unload inside the velocity reversals.

Modified Eaton's method

The normal compaction parameters are developed by the linear interpolation due to lack of offset data. The variable overburden gradient is used to predict the pore pressures and interpretations are discussed.

Details of the work done

(1) Two seismic sections on the synclinal and flank part of the Atharamura namely A and B were taken .The velocities used in this work were P-wave Common Depth Point (CDP) stacked velocities. Velocity data from the 14 different CDP points were used for the pore pressure predictions.
(2) As the Atharamura Stratigraphy thickness is not well known, bulk density of the formation was calculated by using the value of $\Delta t_{max} = 62.5 \mu s/ft (for\ shale)$, $\Delta t_f = 200\ \mu s/ft$ (for water) in the Equation (8) (ENI, 1999).
(3) Pore pressures were predicted using both Modified Equivalent depth and Modified Eaton's methods to select the best prediction method.
(4) Predicted pore pressures were compared with measured pore pressures of other drilled wells in Tripura. The locations of wells taken for this comparative study are Agartala Dome, Tichna, Kunaban, Khubal and Kathalchari (Table 3).

Interpretations from pore pressure predictions

(1) Based on comparison, Eaton's method predicted pore pressure gives smooth pressure transition while equivalent depth method gives fluctuated pore pressures with depth (Figure 3b). Though the modified equivalent depth method is expected to accounts for unloading of effective vertical stress, the magnitude of unloading is found to be less, compared to the Eaton's method.
(2) Over pressure starts in the shallow depths (1500 to 2000 m) in synclinal (Table 1) part while in flank part, it starts at deeper (Table 2) depths (4000 to 5000 m). Pore pressure gradient attains the maximum value of 1.06 psi/ft in the synclinal part and 0.8 psi/ft in the flank part. Velocity reversals were frequently observed (Figure 4) on both flank and synclinal part of Atharamura but unable to confirm the cause of fluid expansion, as the density log data are not available.
(3) Prediction shows that (Tables 1 and 2) over pressured formation continues up to the depth of 10,000m which is practically impossible as there is no sedimentary rocks that exist below the depth of 6000 m (Figure 3b).This is because the entire pore pressure prediction is based on the assumption that velocities have the linear relationship with depth. But this assumption is not valid at deeper depths (Aki and Richards, 1980) as the linear relationship between propagation velocity and depth vanishes (here below 6000 m).

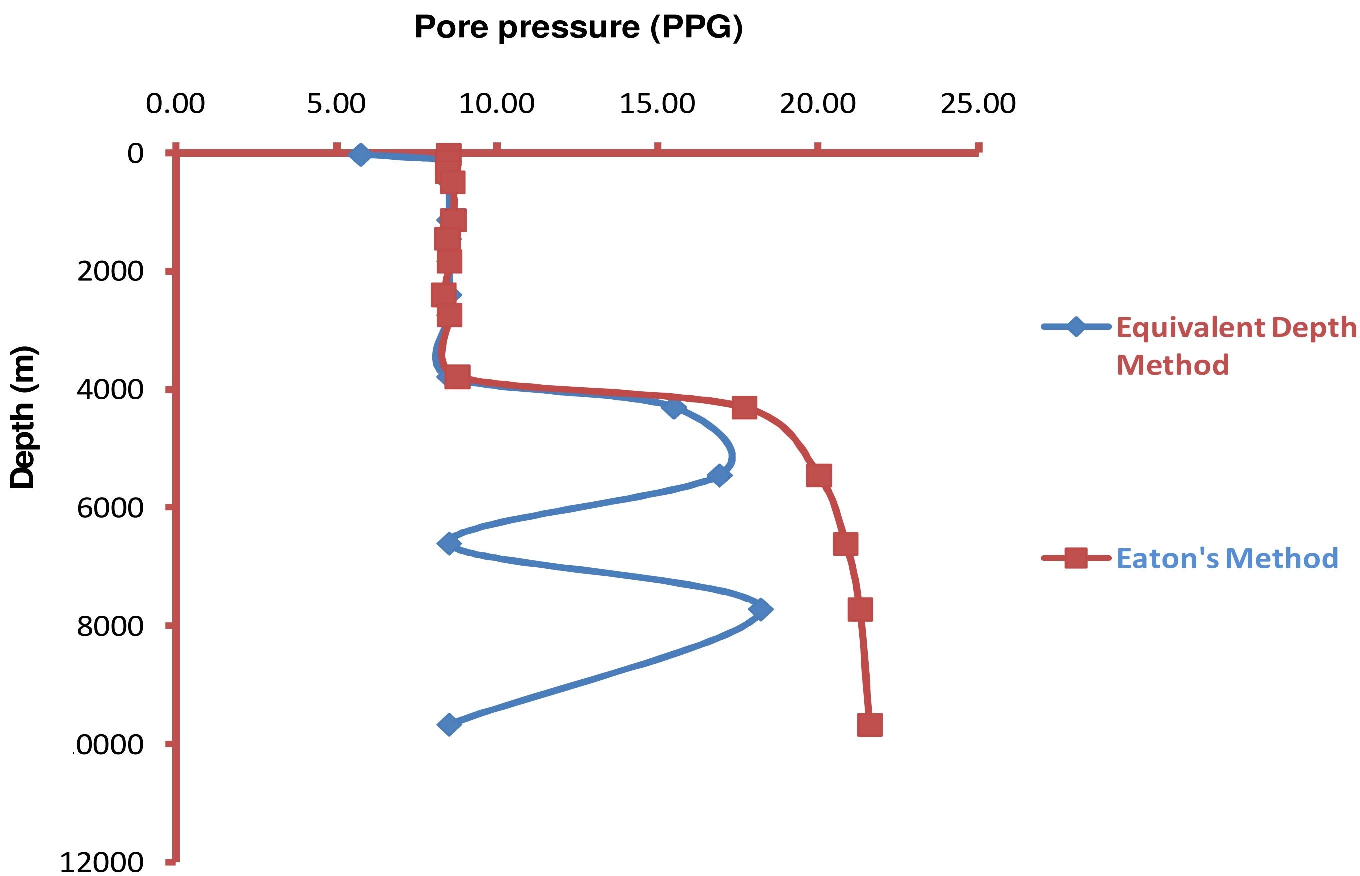

Figure 3b. Prediction results.

Table 1. Depth range of over pressure on the Atharamura syncline.

CDP	Modified equivalent depth method (m)	Modified Eaton's method (m)
1	1123 - 2424, 6000 - 10000	1237 - 10000
2	872 - 1666, 2340 - 6064, 6100 - 10000	1666 - 10000
3	2254 - 4630, 5841 - 9367	1600 - 10000
4	3556 - 8356	3787 - 10000
5	3374 - 6791	2100 - 10000
6	2146 - 3862 , 4805 - 6618	1588 - 10000

Table 2. Depth range of over pressures on Atharamura flank.

CDP	Modified equivalent depth method (m)	Modified Eaton's method (m)
1	4904 - continues up to 10000	2654 - 10000
2	2631 - 3900	1608 - 10000
3	5600 - 10000	4218 - 10000
4	8435 - 10000	5360 - 10000
5	8435 - 10000	5360 - 10000
6	2260 - 3900, 8435 -10,000	4416 - 10000
7	8435 -10,000	5360 - 10000
8	8500 - 10,000	3369 - 10000

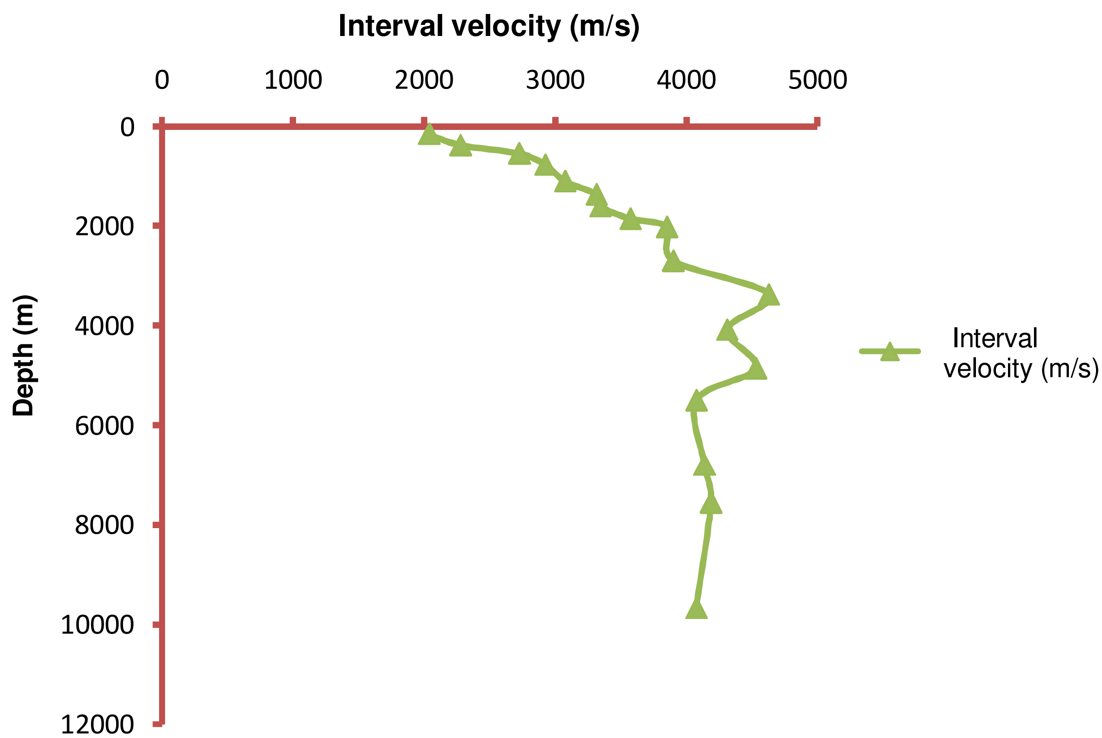

Figure 4. Velocity reversals.

COMPARATIVE STUDY

To get a better understanding of the pore pressure succession in this region, predicted pore pressures were compared with the offset wells measured pore pressures. Offset wells taken for this comparative study are Tichna, Kunaban, AD-6, Khubal, Agartala Dome, Kathalchari. Except Khubal other wells were located at the west of the Atharamura .Pore pressures in the offset wells were measured by Repeat Formation Tester (RFT)

When the offset well measured pore pressures were compared with predicted pore pressures of Atharamura an excellent match is observed between them. Out of 14 Common Depth Point's (CDP) predictions 8 of them show a similarity with offset well measured pore pressures. This should be stressed here that there is no accurate match but resemblance between the predictions and measured pore pressures. This can be observed well with the help of the figures shown (Figures 6, 7, 8 and 9).

It should be remembered that this pressure match cannot be taken as assurance for the accuracy of the predictions. Moreover, it is not necessary for the predictions to match with pore pressure of the offset wells which are located far away from Atharamura and in different geological conditions. For example one of the offset well locations, Agartala Dome is a subsurface structure while Kathalchari, Tichna, Khubal wells were located in different anticlines exposed to the surface. But this match gave an opportunity to explore the most possible reason for the pore pressure succession in the Tripura Region (Figure 5).

Measured pore pressures of wells drilled on the top of the other anticlines match with predicted pore pressures on the flank and synclinal part of the Atharamura. This indicates the presence of single pore pressure source in the sub-basin. As the anticlines in Tripura become steeper from west to east, the over pressure measured on the top of the other structures located in the western part matched with predicted pressure of the Atharamura structure in eastern part .The increasing steepness from west to east could be the main reason for the over pressure migration to the deeper depths in the Atharamura. Unlike in the flank and syncline part, hydrocarbon bearing Middle Bhuban formation is exposed up to the surface on top of the Atharamura anticline. Thus it offers the permeable flow path for pore fluids to the top of the Atharamura. If the impermeable seal is available on top of the anticline, overpressures, which are encountered at deeper depths in flank part could be expected at shallow depths on the top of the anticline.

Conclusion

Pore pressure prediction from seismic velocities is not only to plan a well but also can be a key to understand the pore pressure profile in the region. In this work, pore

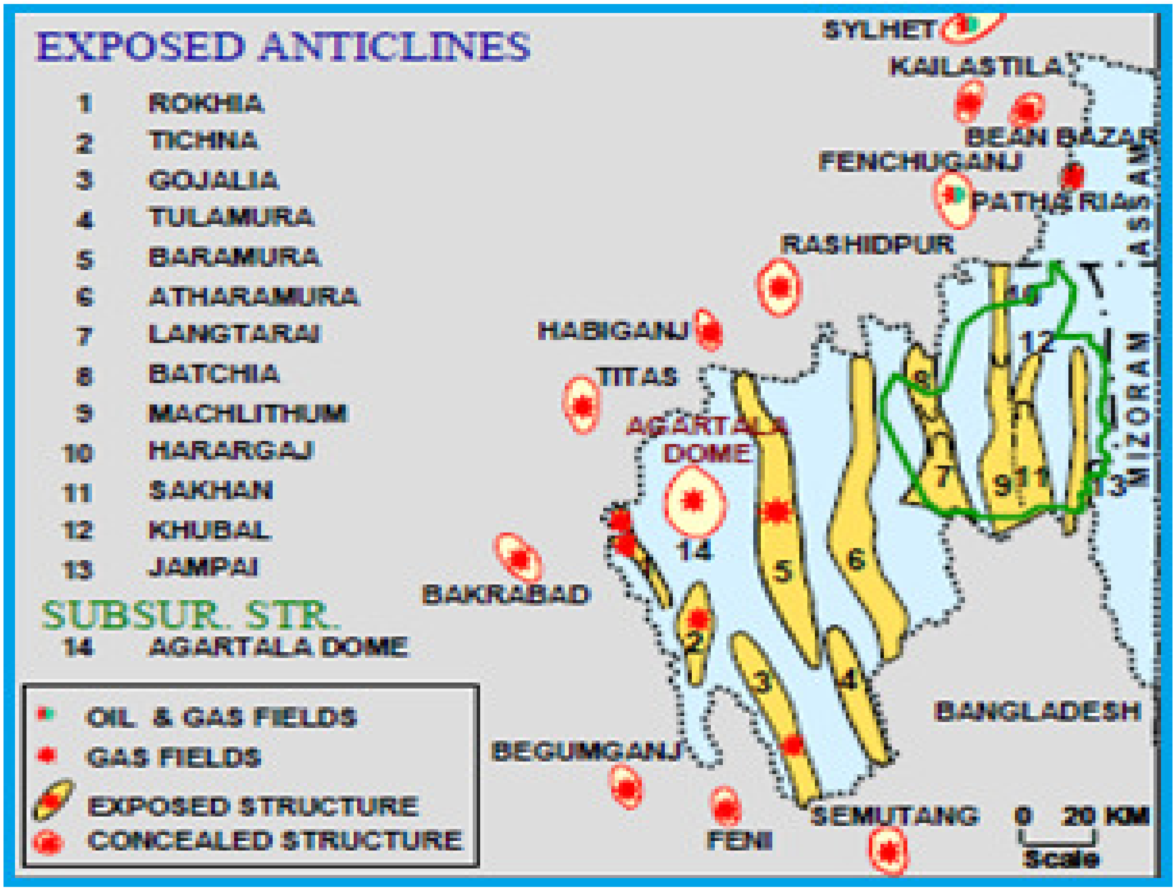

Figure 5. Anticlines of Tripura.

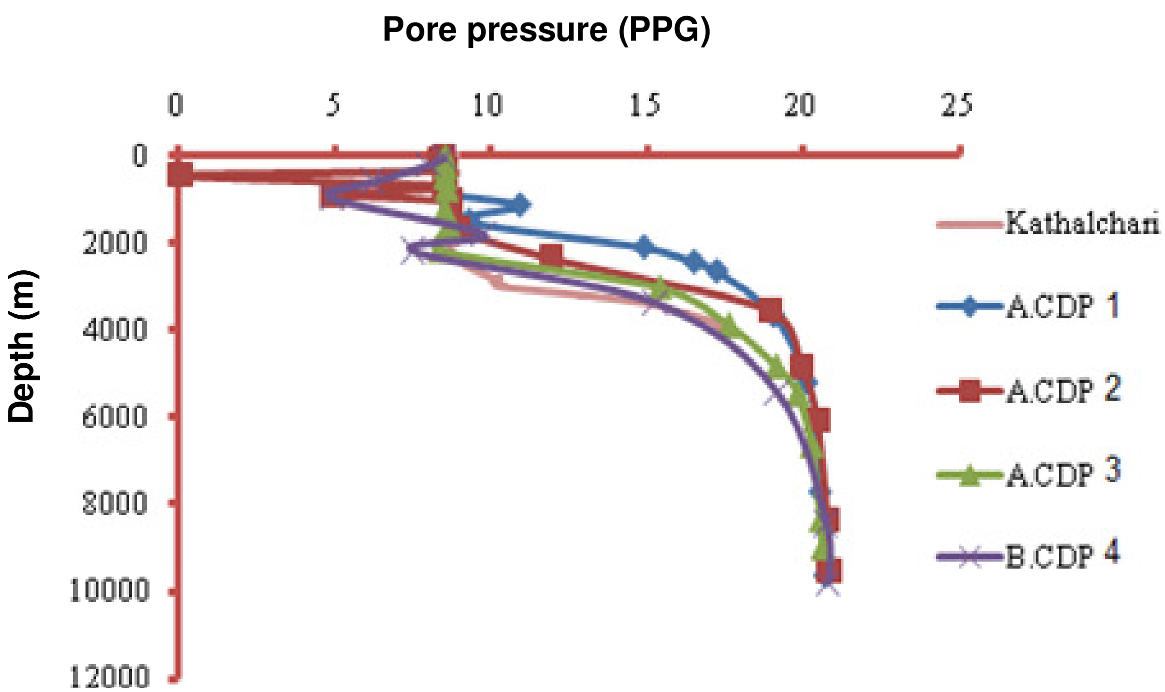

Figure 6. Kathalchari measured pore pressures Vs Predicted pore pressures.

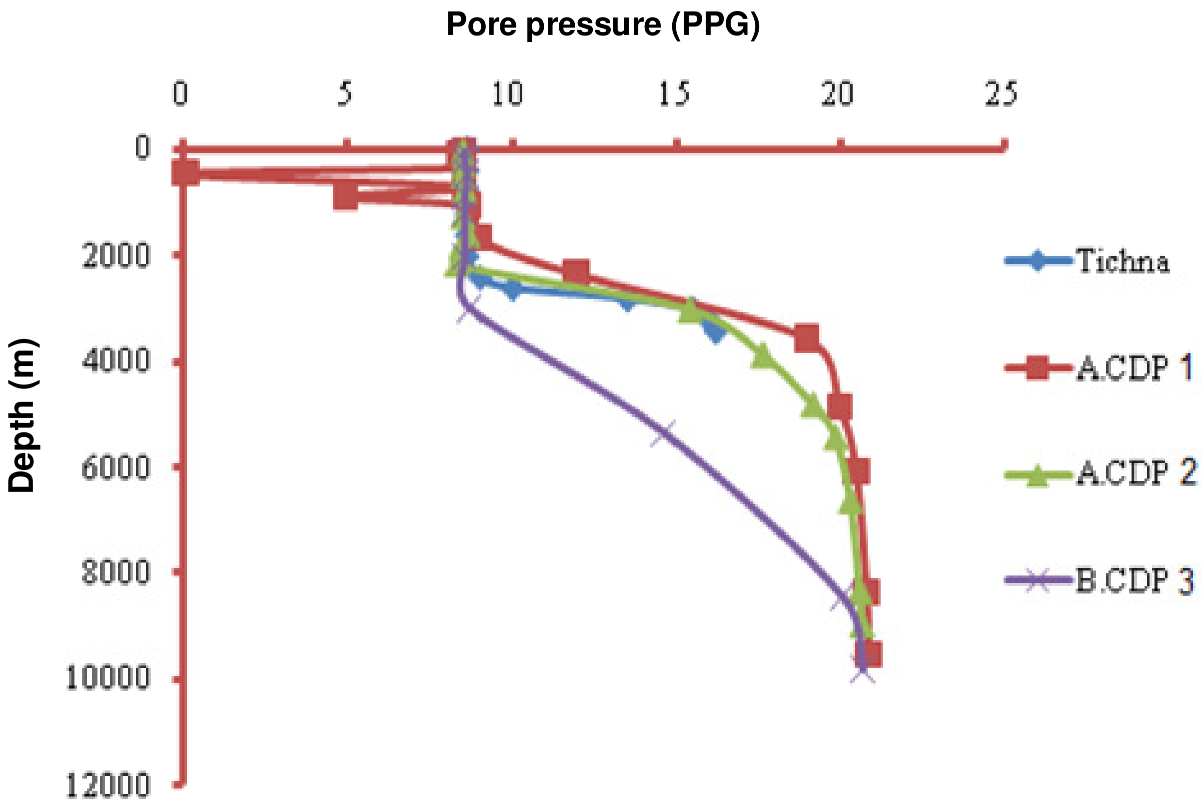

Figure 7. Tichna measured pore pressures Vs Predicted pore pressures.

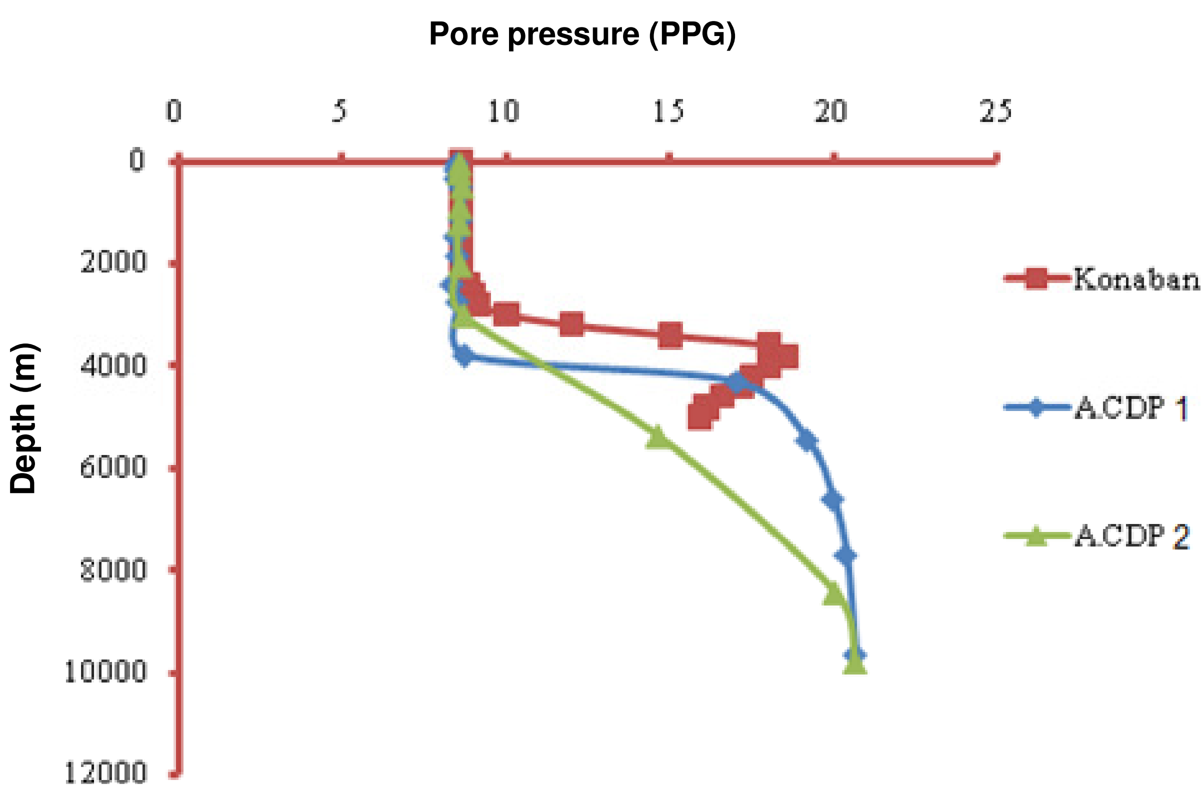

Figure 8. Konaban measured pore pressures Vs Predicted pore pressures.

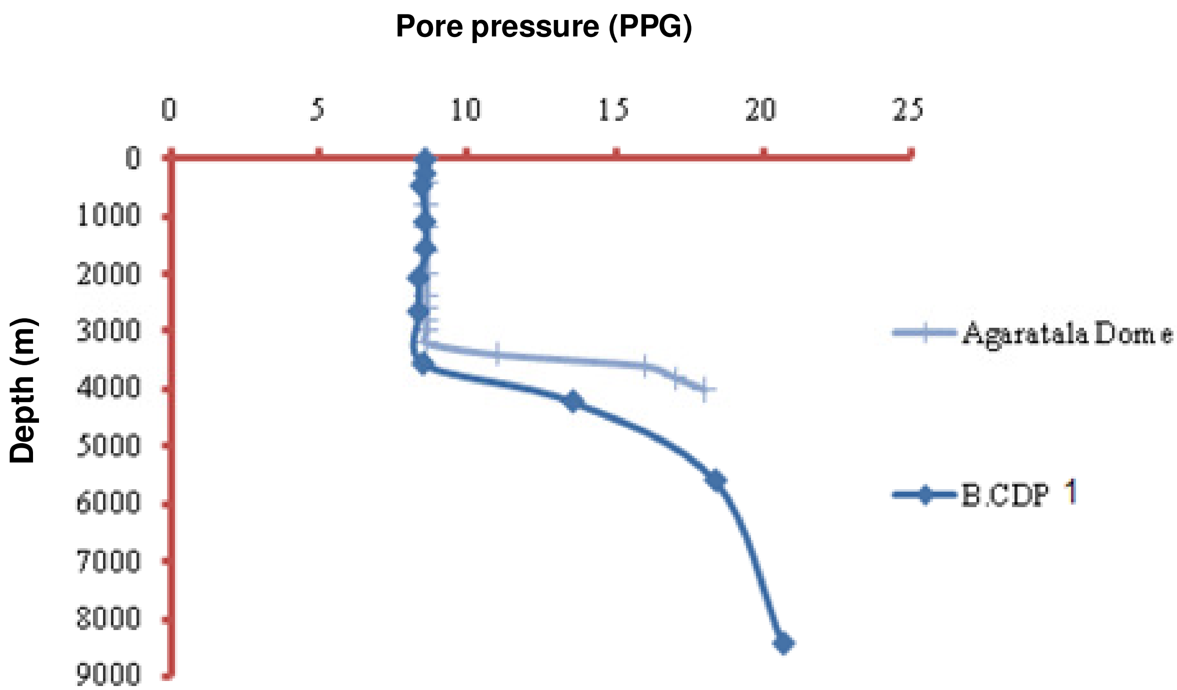

Figure 9. Agartala Dome measured pore pressures Vs Predicted pore pressures.

pressure prediction on Atharamura anticline leads to the encouraging observations and clear understanding of pore pressure in this region. Pore pressure predictions on the synclinal and flank part lead to the following possible facts:

(1) Modified Eaton's method is the best suitable pore pressure prediction method for this region. But it is recommended to use Modified Equivalent depth method along with Modified Eaton's method to avoid the uncertainty where seismic velocities are the only available pre-drill tool to predict the pore pressures.
(2) Seismic velocity plateaus confirm the cause of over pressure to be due to under compaction.
(3) From the comparison with offset well measured pore pressures it is found that the region is characterised by single pressure source and over pressures migrated to the shallow depths from West to East in the Tripura sub-basin.
(4) As the hydrocarbon bearing Middle Bhuban formation is exposed on top of the anticline, there is huge possibility for the presence of overpressure at shallow depths, provided impermeable seal on the top.

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